Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Color Imaging for Accurate Color

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Abstract: The term colorimetric imaging is used to describe the process of recording an image where the pixels represent quantitatively accurate color information. This talk will give the background for colorimetric imaging, why it is important, the hardware and software currently in use and the research problems that are of interest. Accurate color recording requires much more than three channels of red, green and blue. Although the eye has only three bands of color sensors in the cones of the retina, this does not mean that an instrument needs only three channels to measure color. Color is more complex and is the result of a continuous spectrum of energy from about 400 nm to 700 nm in wavelength. To accurately record the color of an object, we need to sample this spectrum with sufficient resolution to reproduce the effects of lighting on the appearance of the scene or object. In addition to maintaining the accurate appearance of objects, the accurate recording of the spectrum is required for many applications, ranging from medical diagnoses to pattern recognition and tracking to quality control of textile and food processing.

Keywords: Color Imaging, Accurate Color.

References:

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Joel Trussell received degrees from Georgia Tech (BS), Florida State (MS) and the University of New Mexico (PhD). He began working in the image and signal processing in 1971. He is currently a professor in the Electrical and Computer Engineering Department at North Carolina State University, Raleigh, NC. During 1978-79, he was a visiting professor at Heriot-Watt University, Edinburgh, Scotland where he worked with both the university and with industry on image processing problems. During 1988-89, he was a visiting scientist at the Eastman Kodak Company in Rochester, NY and 1997-98 was a visiting scientist at Color Savvy Systems in Springboro, OH. He was a Visiting Fellow Commoner at Trinity College Cambridge University in 2007 and in 2015, and a visiting scientist with Hewlett-Packard Labs in 2008. From 2002 to 2010, he served as Director of Graduate Programs for the ECE Department. He is a past associate editor for the Transactions on ASSP and the Signal Processing Letters. He is a past chairman of and long serving on the Image and Multidimensional Digital Signal Processing Committee of the Signal Proceesing Society of the IEEE. He is currently Editor-in-Chief of the Proceedings of the IEEE, where he has been on the editorial board is 2006. He is Fellow of the IEEE and has shared the IEEE-ASSP Society Senior Paper Award (1986 with M.R. Civanlar) and the IEEE-SP Society Paper Award (1993 with P.L. Combettes). He is the author of two texts: Fundamentals of Digital Imaging (with M. J. Vrhel) and Mathematics: The Language of Electrical and Computer Engineering (with Y. Viniotis).

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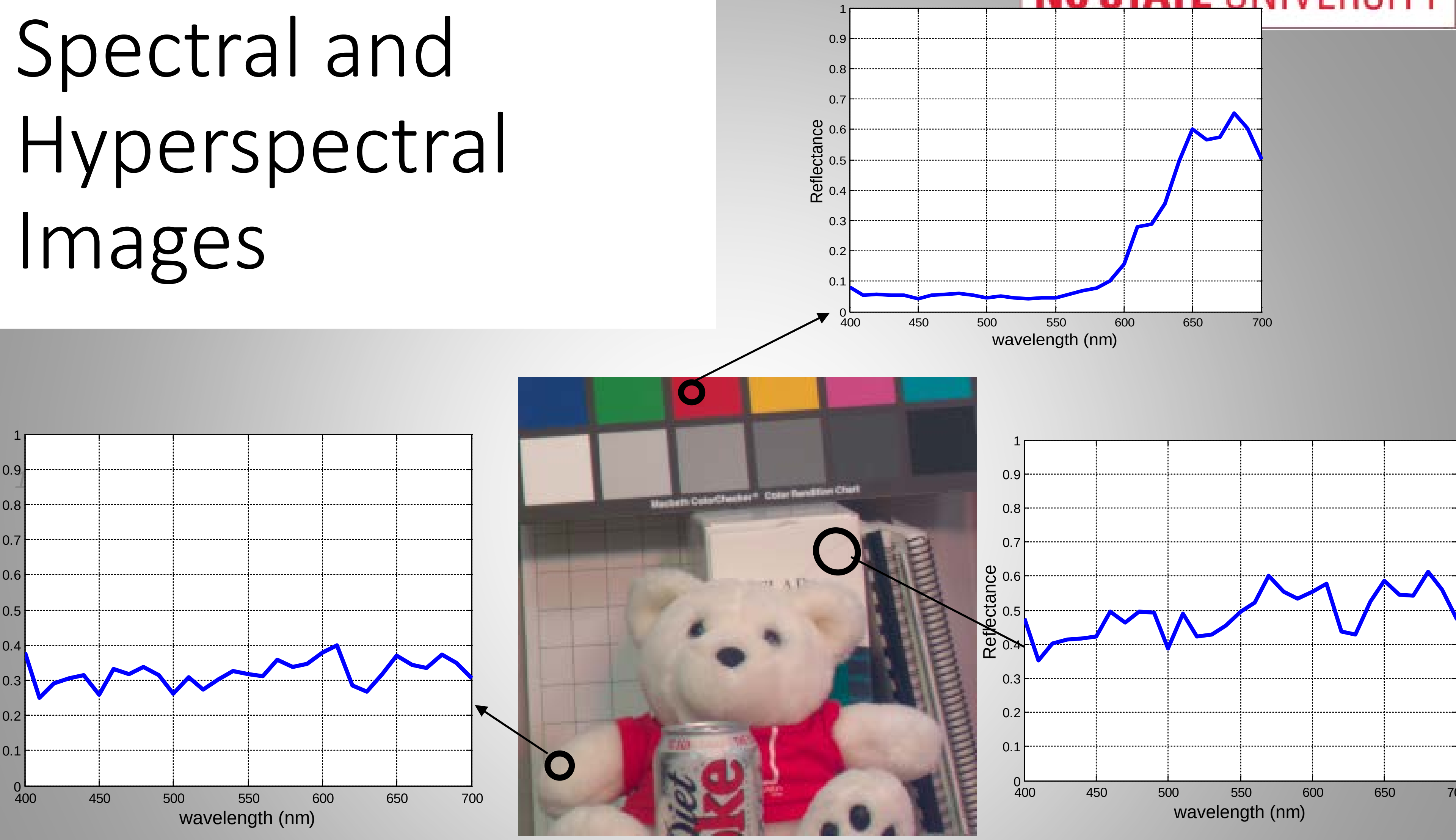
What is Accurate Color?

The quantitative description of the object so that any observer can determine how that object would appear under any illumination.

Topics:

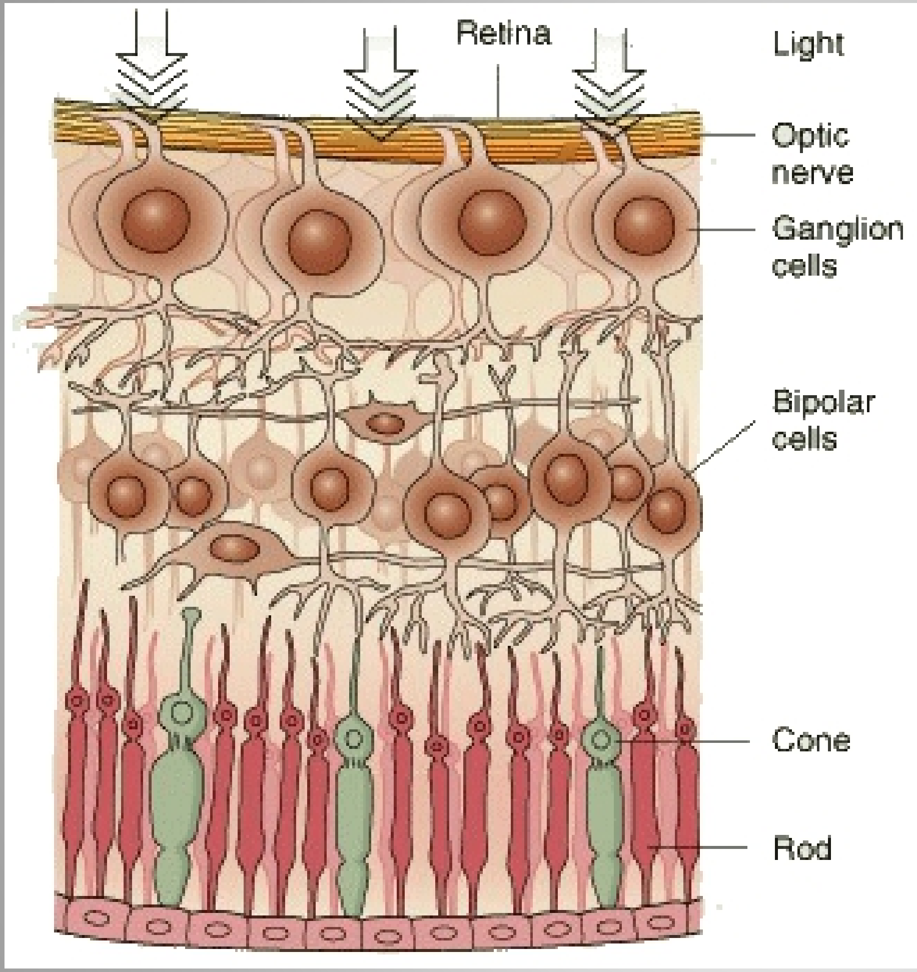
- *Spectral description of color*
- *Recording of color*
- *Instrumentation*
- *Cameras*
- *Applications*
- *Research problems*

Spectral and Hyperspectral Images

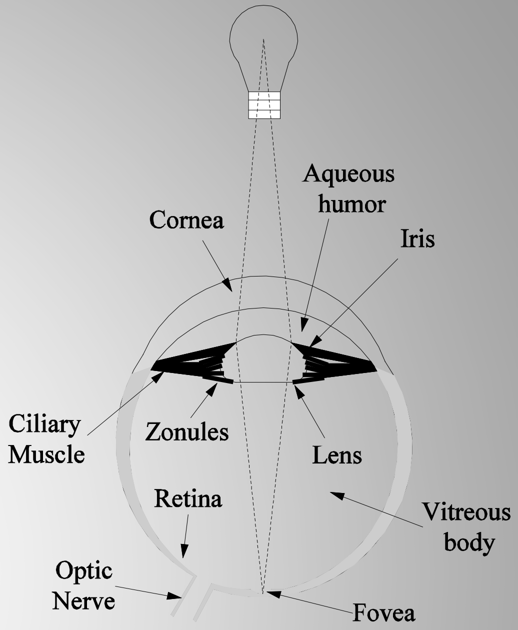


15-200 channels

Human Visual Sensitivity: 380nm – 760nm

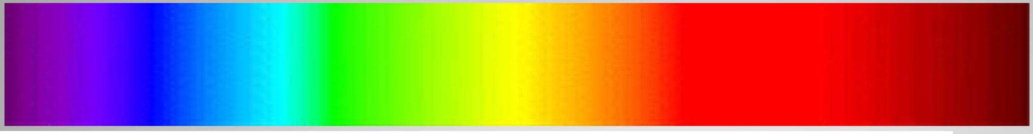


http://www.thetwentyfirstfloor.com/?p=942



Cones: three types for color vision at higher illumination levels

Rods: one type used for low illumination



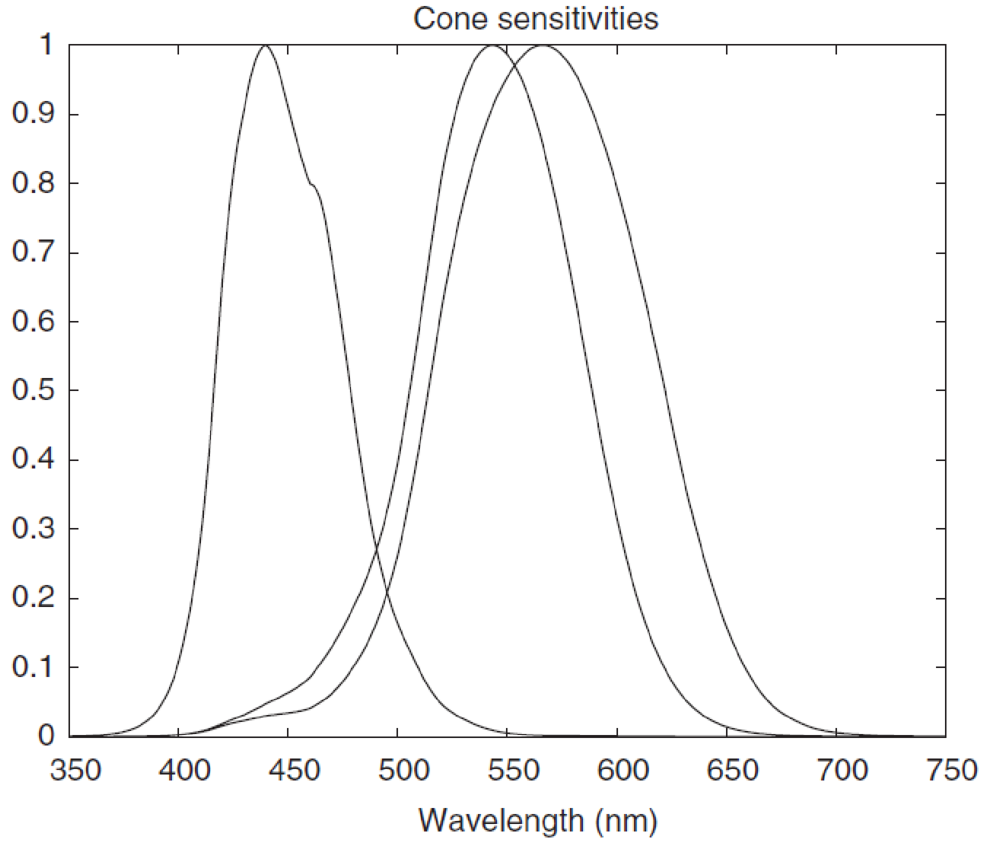


Figure 8.8. Cone sensitivities of the human eye.

Sensitivity of Cones

Long wavelength
Medium wavelength
Short wavelength

Color Measurement Devices

Spectroradiometer – measures radiant source (visible spectrum)

Measures radiant spectrum from UV to near IR

Applications :
Precise colorimetry, lighting, LEDs, calibrating displays and colorimeters, chemical characterization, paints and goniometry

Color Measurement Devices

Spectrophotometer – measures reflectance and transmission (visible spectrum)

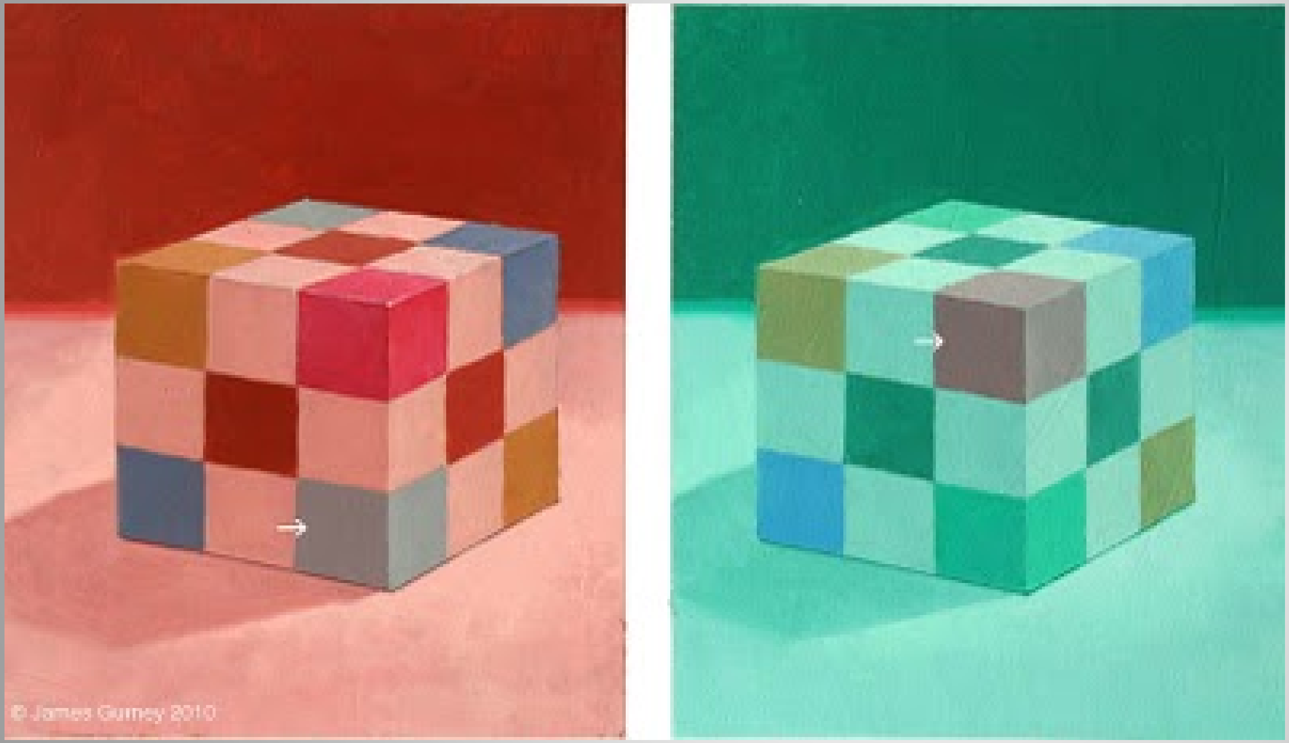
Applications :
Precise colorimetry, textiles, printing, paints, gloss, food, packaging, chemical processes

Color Image Recording Devices

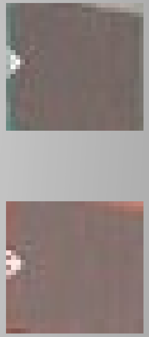
- Digital still camera
- Digital video camera
- Document scanner
- Book scanners

All are three-band recorders

Color Constancy: Your vision system will adjust to the lighting that illuminates an object, but the camera will not!



Top Red

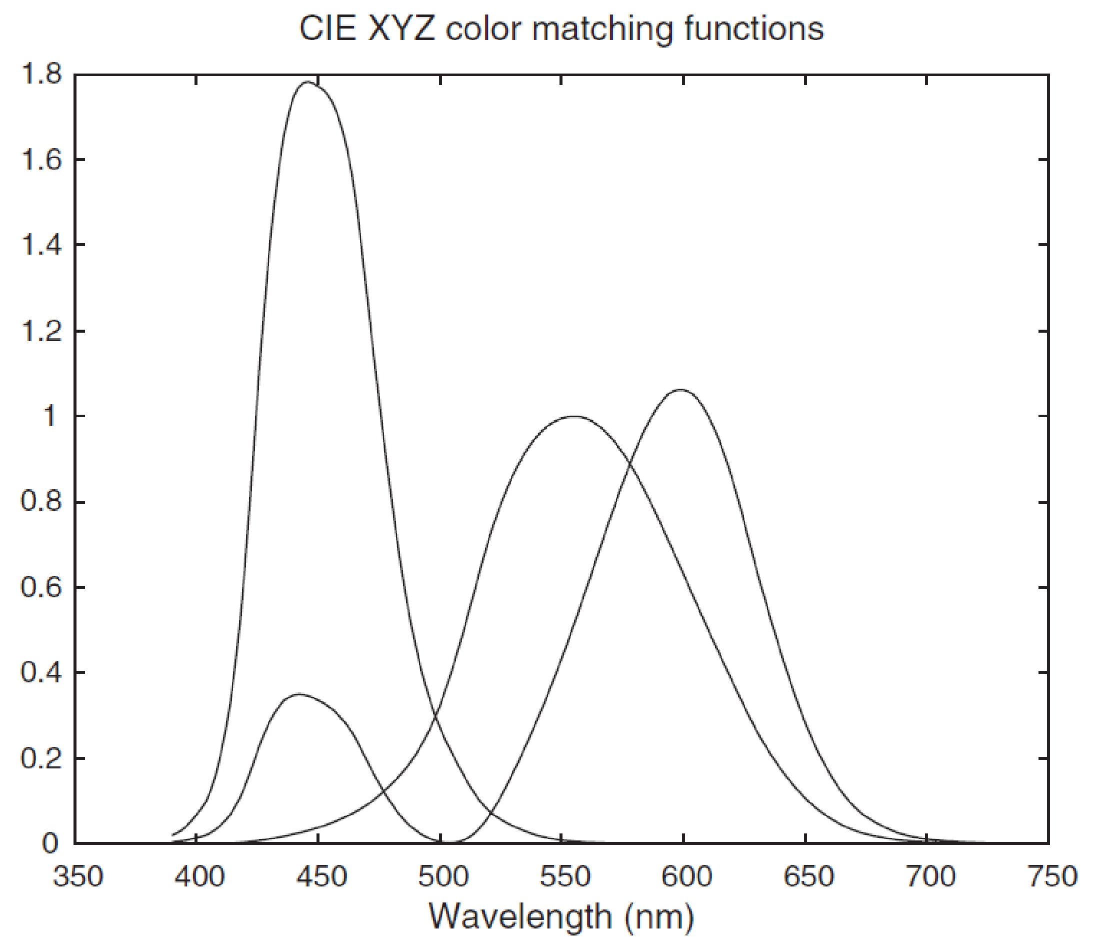


Bottom Cyan

For accurate color, we need to measure the reflectance of the object, so we can reproduce its color under any illumination

Colorimetry

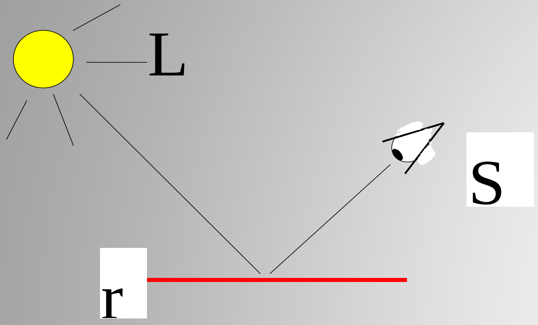
Three CIE XYZ Color Matching Functions



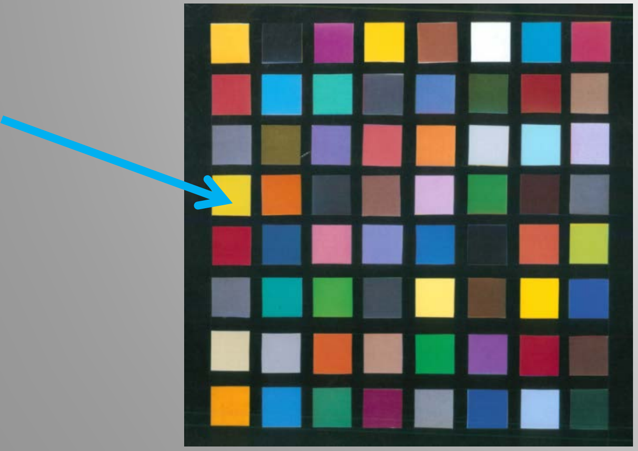
Everyone uses a standard transformation of the average cones sensitivities, defined by the CIE (Commission internationale de l'éclairage)

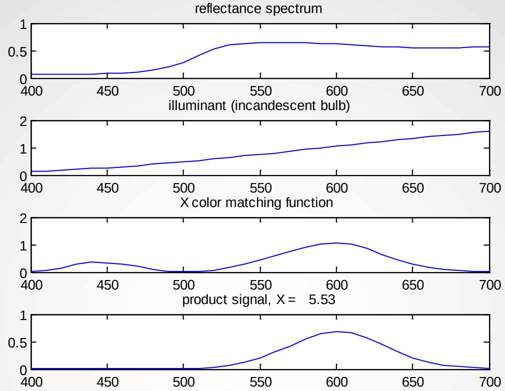
Effect of Illumination:

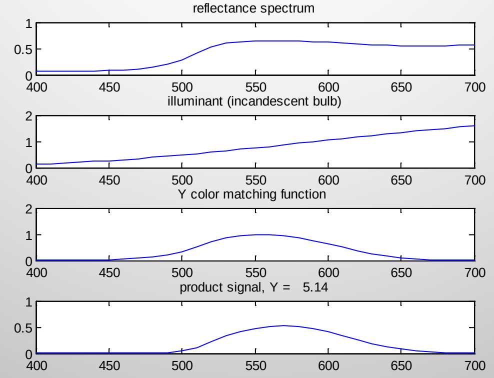
The spectrum of the illuminant effectively changes the color matching functions

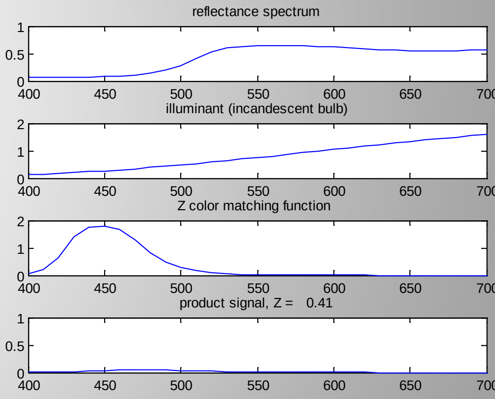


$$c = S^T L r$$





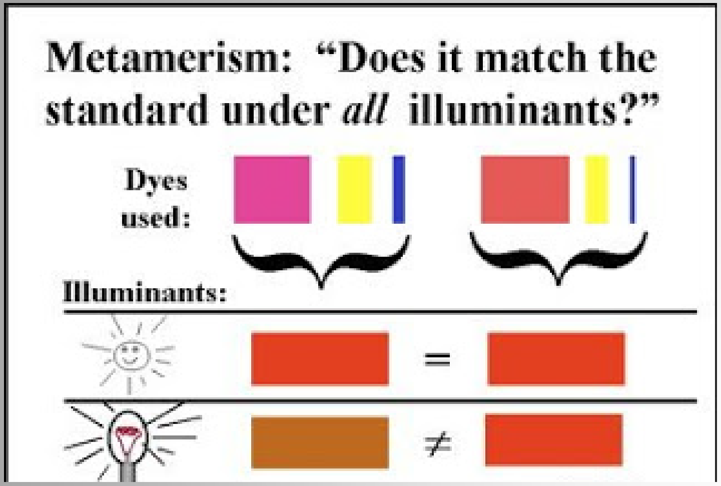




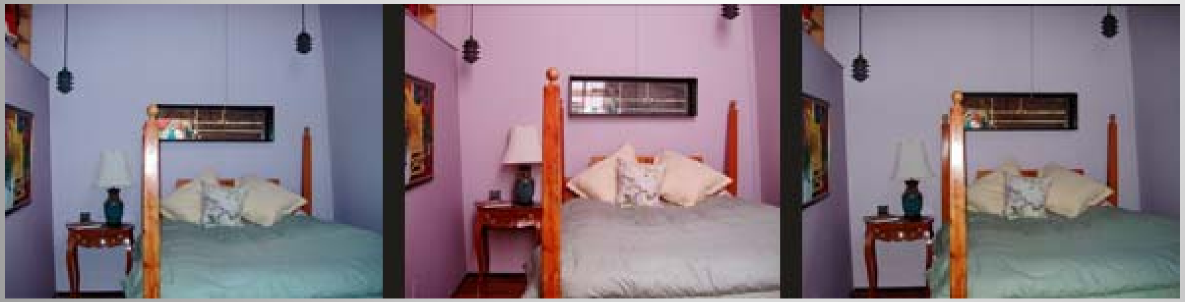
(X,Y,Z) = (5.53,5.14,0.41)
(x,y,z) = (0.50,0.46,0.04)
With incandescent light

Effect of Illumination:

Metamerism: objects look different under different illuminations

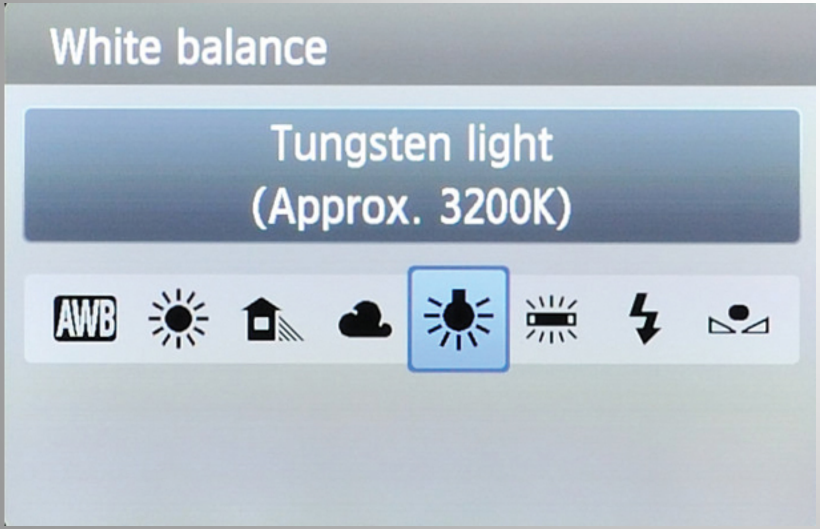

Metamerism: "Does it match the standard under *all* illuminants?"
Dyes used:
Illuminants:
=
≠

http://knowledgeandfashion.blogspot.com/2011/07/metamarism-in-colour-matching-flare.html



Photography

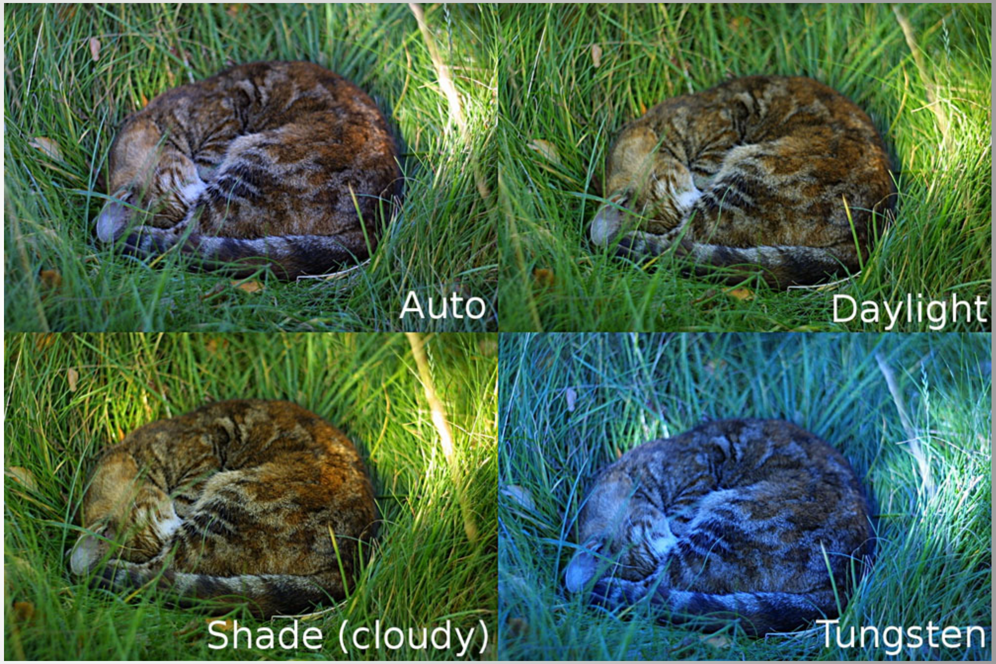
Cameras: Try to guess the lighting (white balance)



White balance

Tungsten light
(Approx. 3200K)

http://www.photoplusmag.com/2012/02/25/interior-photography-best-canon-dslr-settings-for-shooting-indoors

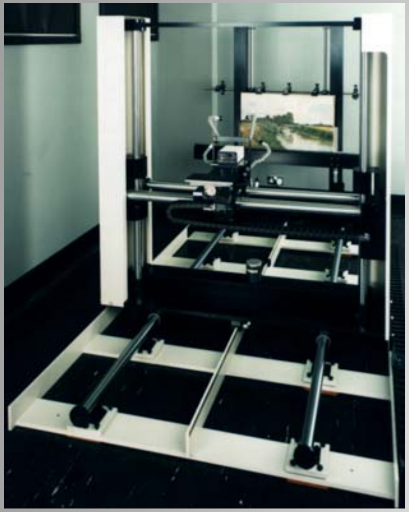


https://arqspin.com/blog/

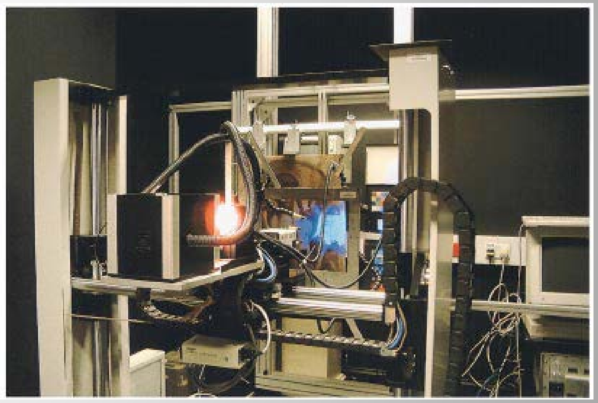
Digital Spectral Cameras

Applications in museum art recording

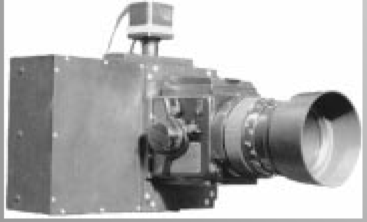
Later printing quality control



VASARI Scanner (1992)
Ecole Nationale Supérieure des Télécommunications
Filter Wheel , Scanner– 7 bands, 3000x2000 pixels



VASARI Scanner (2000) ENST
Filter Wheel , Scanner– 12 bands, 3000x2000 pixels



MARC CCD Camera (2001) ENST
CFA 3 bands, 20k x 20k pixels, micropositioning
compensate for CFA, macropositioning scans image

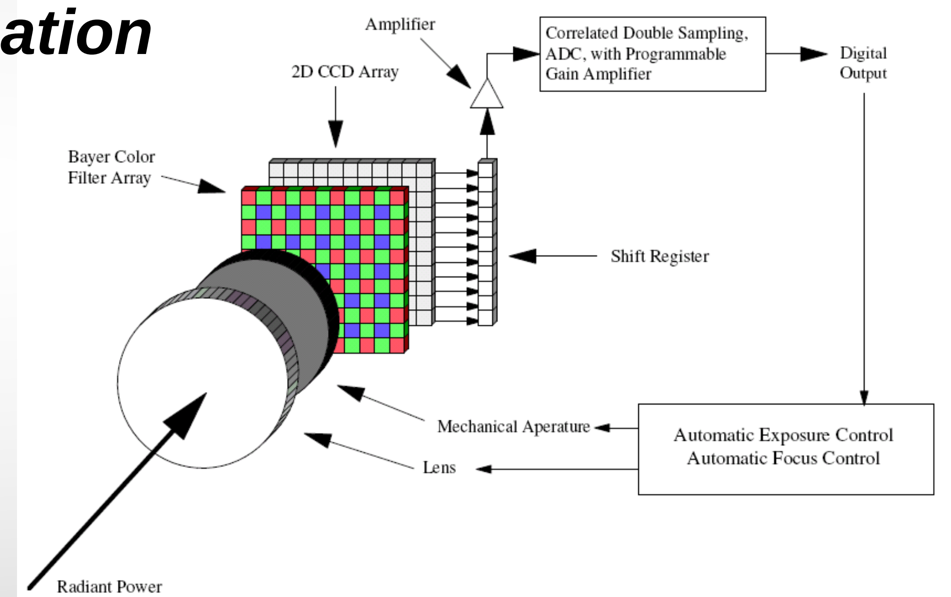
Digital Spectral Cameras

Modified Sinar Camera
Rochester Institute of Technology
2 filters + 3-band CFA, 6 bands, interpolated to 380-730nm, 4080x5440 pixels micropositioning used to compensate for CFA

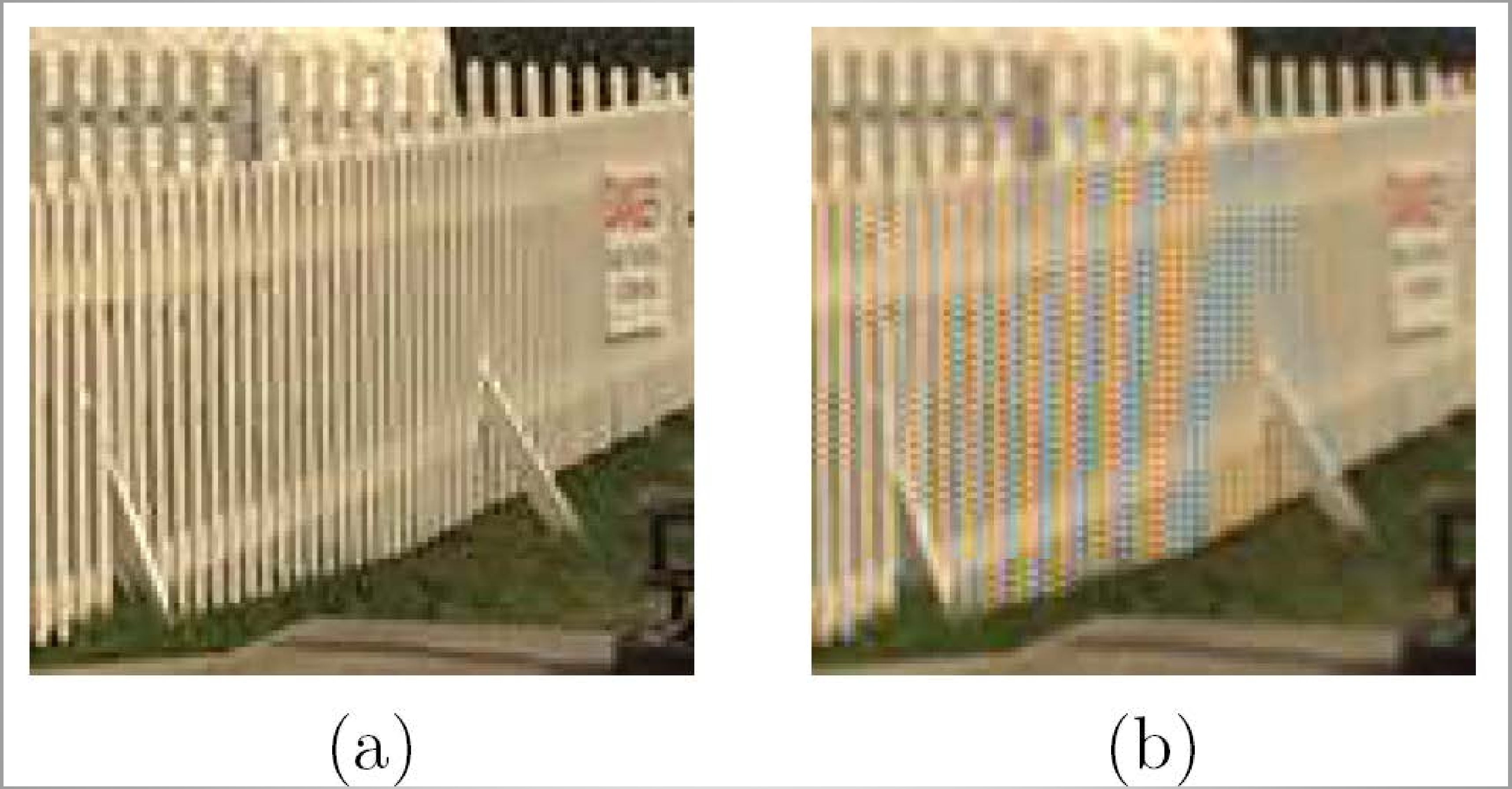
Tricor Imaging Spectrophotometer
Silicon CCD
1280x960
Filter wheel
Interpolated to 380-780nm; 20nm
60 seconds

Digital Still Camera – Pipeline

1. ***Exposure adjustment***
2. ***Optics/focus***
3. ***Initial image capture/digitization***
4. ***Dark noise removal***
5. ***Uniformity adjustments***
6. ***Demosaicking***
7. ***White balance***
8. ***Appearance adjustments***
9. ***Compression/file formatting***



Demosaicking – Bilinear Interpolation



Original- high resolution

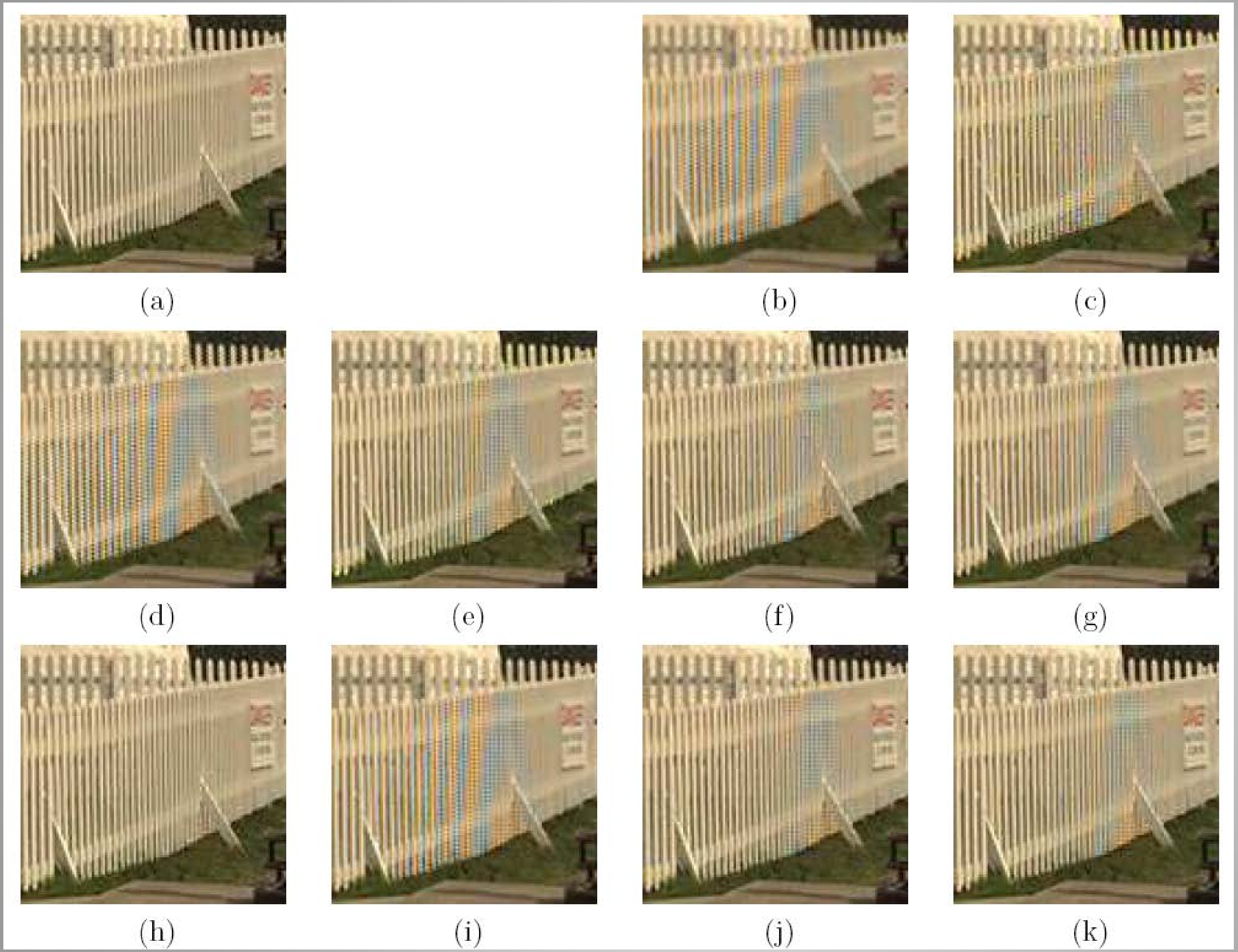
Bilinear interpolation of mosaicked data

Demosaicking Approaches

Use correlation between bands but avoid interpolation across edge boundaries

Estimate edge gradients first then use these to weight interpolation of adjacent bands. May use appearance related properties to determine the color space in which to interpolate.

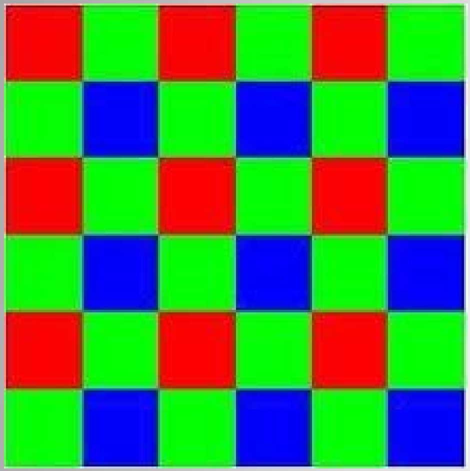
Use of local/global statistical characterization to enforce constraints or properties



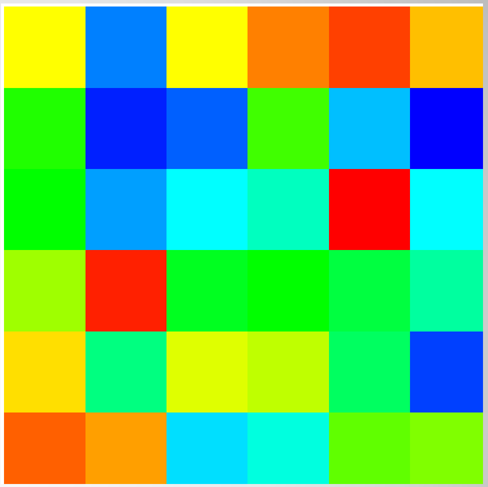
Comparison of several demosaicking methods – Courtesy of Bas, Gunturk, Altunbasak, Mersereau, Shafer

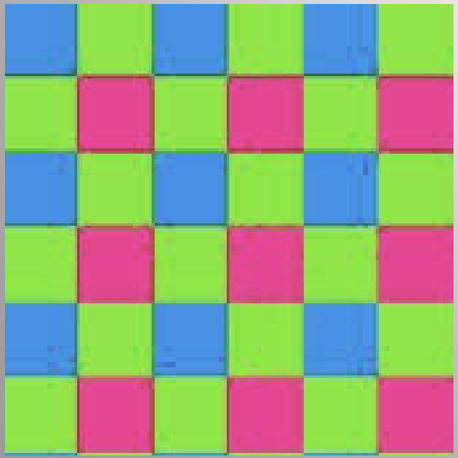
Mosaic Patterns for Color Filter Arrays (CFAs)

Bayer Array 3 bands



Hyperspectral Array 36 bands





Bayer Array + Filtered Array
6 bands

Demosaicking Hyperspectral Arrays

Spectral estimation using multiple bands is well understood.
For low spatial frequency images, the estimates will be good.

Combining multiple bands for sub-block resolution is a problem.

The usual strategy of edge detection using the green band is not applicable

Edge detection is still a problem that will need to be addressed for sub-block resolution

Statistical characterization of the various bands and their correlations need to be addressed.

Color Filter Arrays - Sensors

Typical Hardware Problems for CFAs

Uniform pixel sensitivity – response of the unfiltered CCD/CMOS elements varies spatially

Temporal pixel sensitivity – response of the sensor elements varies with temperature

Nonuniform pixel filters – all filters for a specific band may not be the same, vary with spatial location

Color filter fabrication errors, limitations

Noise may be both spatially varying and signal dependent , as well as temperature dependent

Colorimetry for Cameras and Scanners

Sensor Filters - they are not equivalent to either the human eye or the CIE XYZ color matching functions, need better control of the transmission spectra

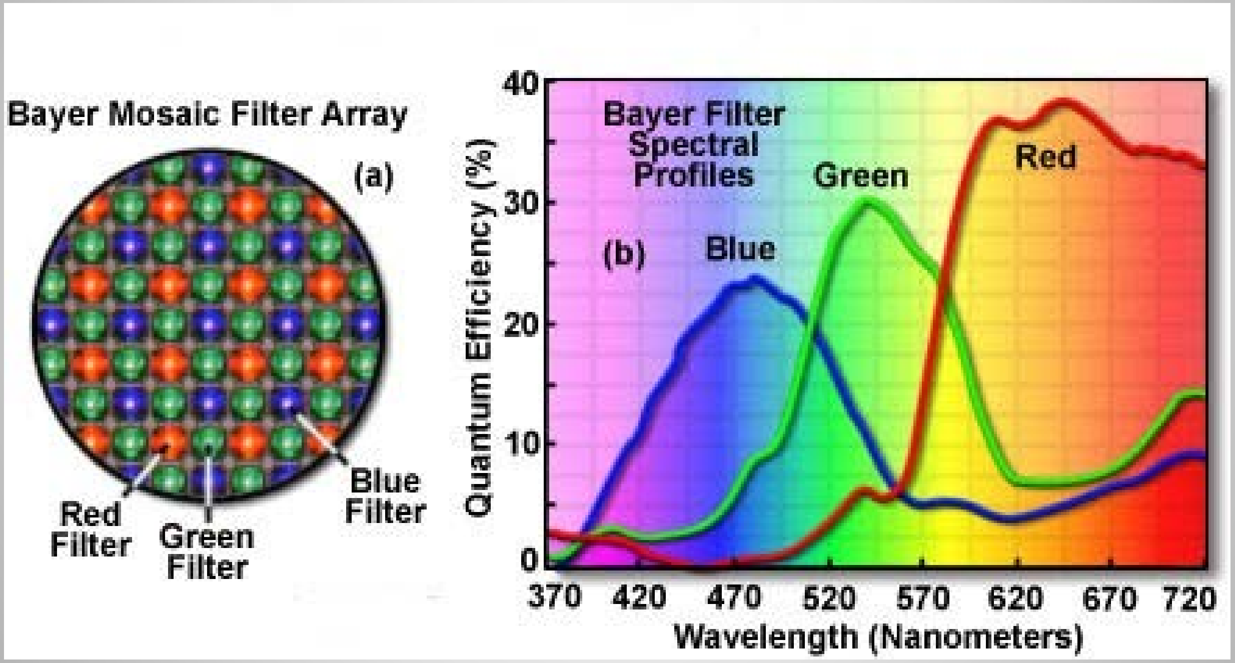
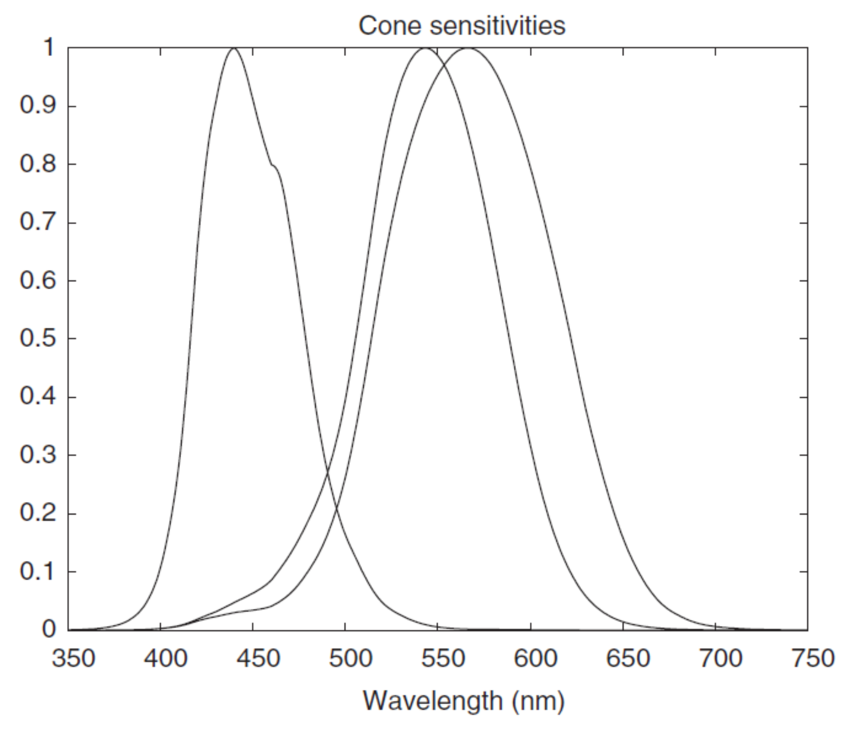
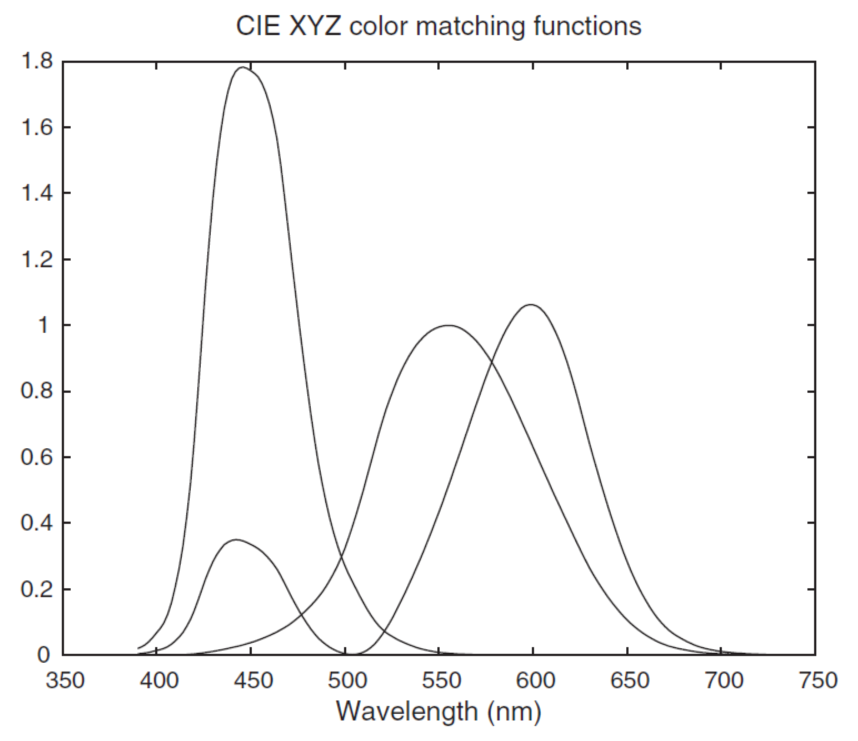


Figure from http://csanet.org

Results of three filter measurements must be transformed by mathematical estimation method to approximate CIE values

Camera filters do not match either the sensitivities of the eye or the CIE color matching functions





This means you cannot capture color accurately

Color Filter Arrays - Sensors

Noise Characteristics for CFAs

Thermal (dark current) noise - Gaussian

Read out noise – transfer of charge in pixel to ADC

Fixed pattern noise (e.g., hot pixels)

Photon response non-uniformity, filter variation

Photon shot noise (Poisson)

Image Characteristics

Stochastic Properties: Types of Noise

Photon Noise:

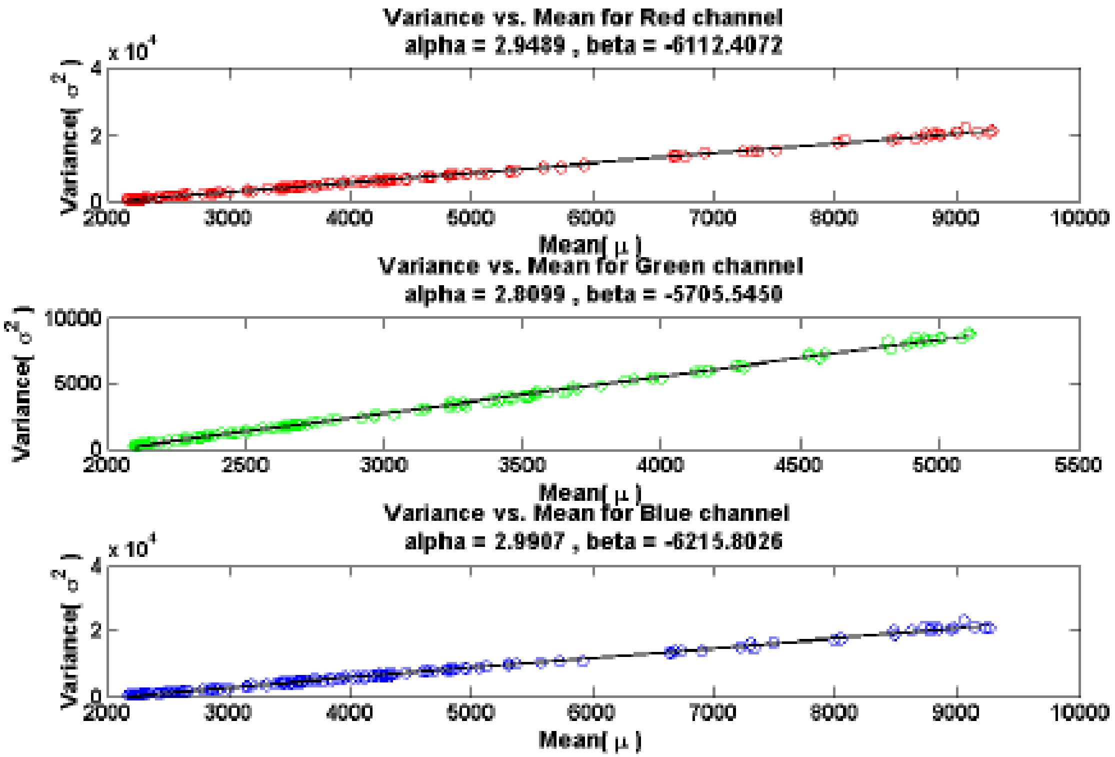


Fig. 6. Variance vs. Mean Curves for Canon Rebel T3 Raw Data

Image Characteristics

Stochastic Properties: Types of Noise

Noise for JPEG sRGB data (after demosaicking):

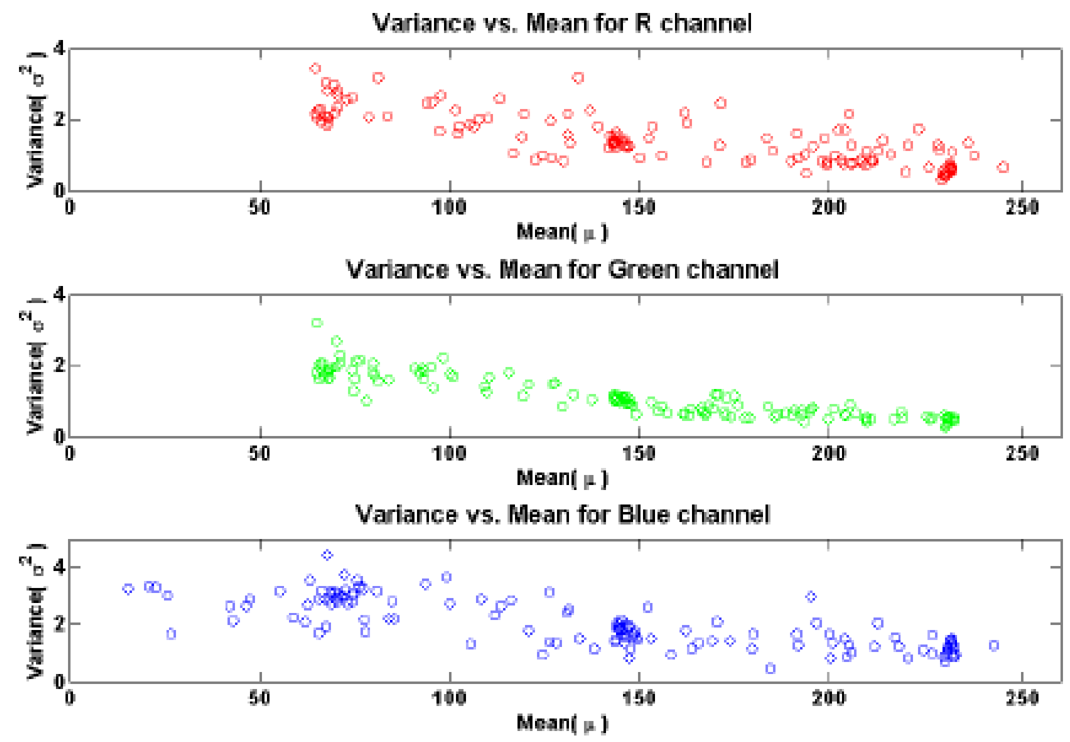


Fig. 5. Variance vs. Mean Curves for Nikon JPEG Data

Color Filter Arrays - Sensors

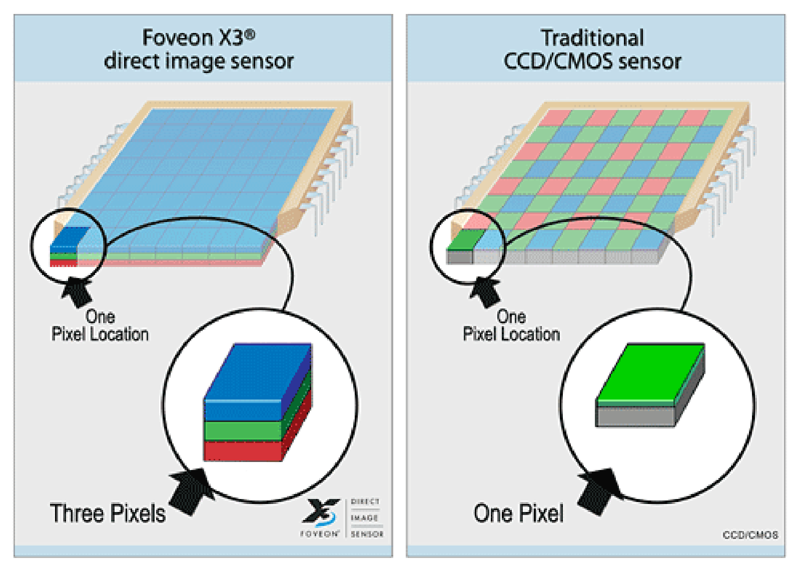
CCD vs CMOS sensors

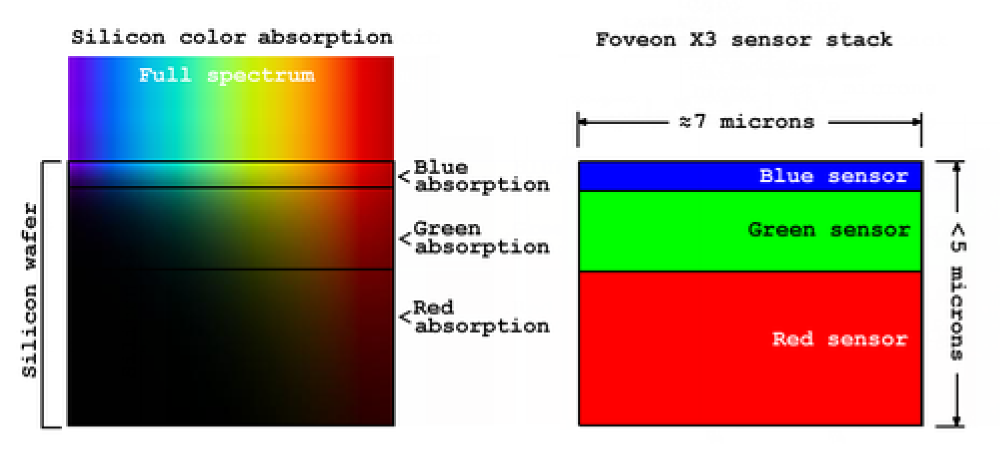
Typically – CCD sensors are less noisy, more sensitive to light, less variability spatially, and use global shutter

CMOS sensors are cheaper, faster, more power efficient, better treatment of over exposure (blooming), and use rolling shutter – problems with video

Color Filter Arrays - Sensors

Foveon sensor (CMOS)





Color Imaging

High dynamic range sensing

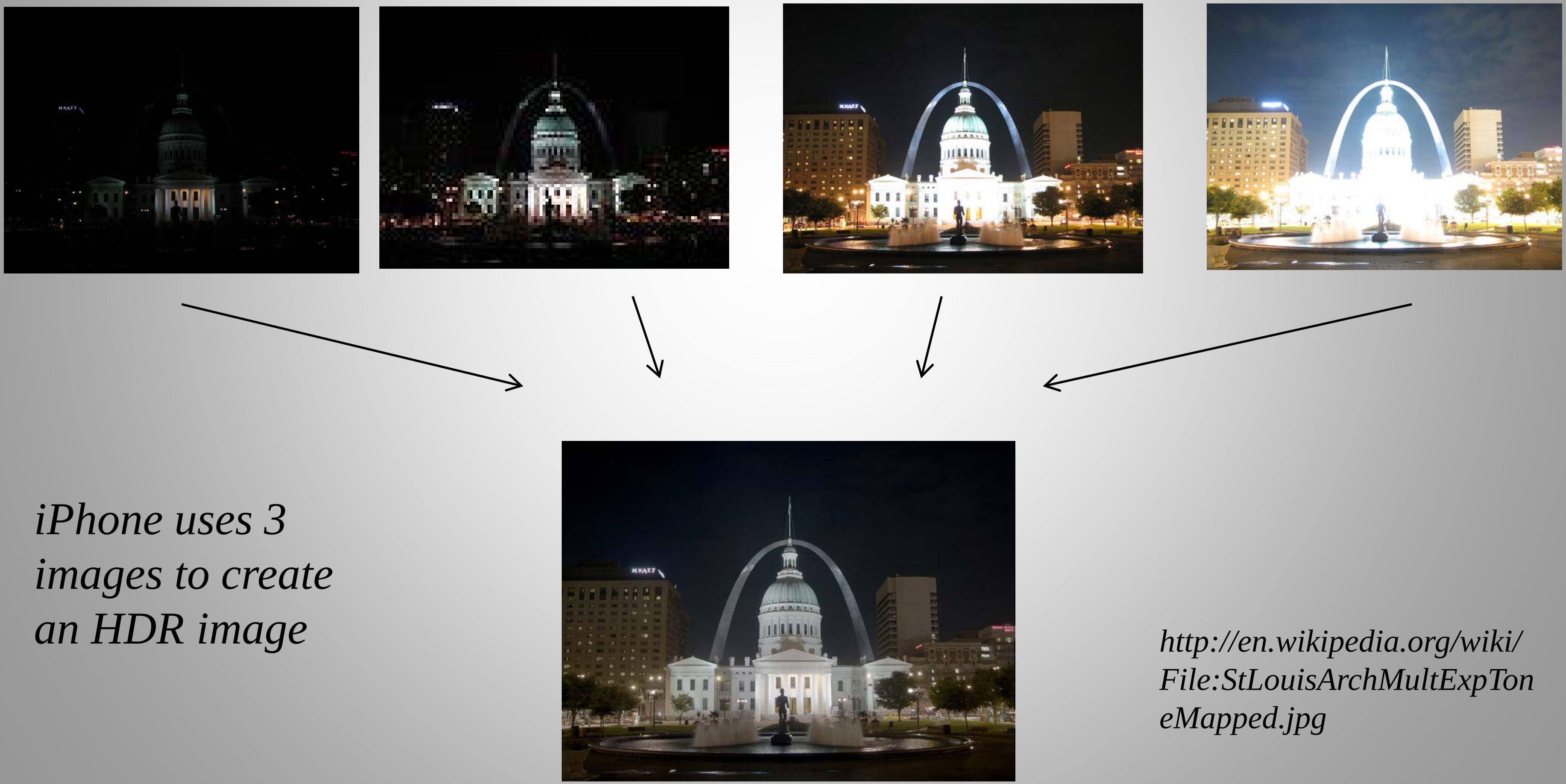
Record accurate information across the entire dynamic range of the scene

Light intensity varies over a range of 10^6

Need to have adaptive sensitivity in light and dark regions – but record the relative exposure

Color Imaging

High dynamic range imaging: example



iPhone uses 3 images to create an HDR image

http://en.wikipedia.org/wiki/File:StLouisArchMultExpToneMapped.jpg

Accurate Color – what's it good for?

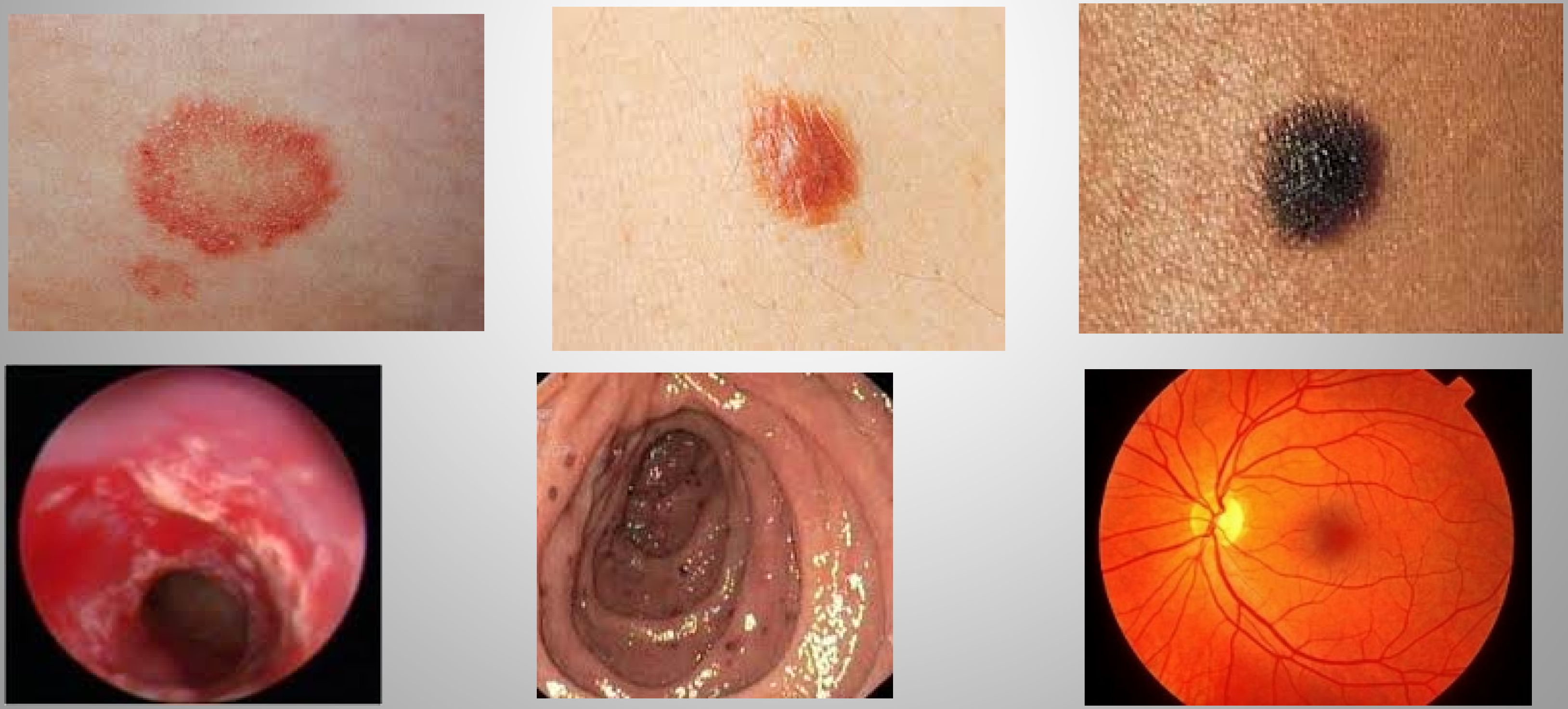
Applications:

- *Improved color recording of natural scenes*
- *Easier archiving of museum art*

Accurate Color – what's it good for?

Applications:

- *Improved documentation and diagnosis of medical conditions that depend on color, e.g., dermatology, ophthomology, endoscopy*



Accurate Color – what's it good for?

Applications:

- *Color quality control of complex patterns, e.g., textiles, printing, packaging*

Accurate Color – what's it good for?

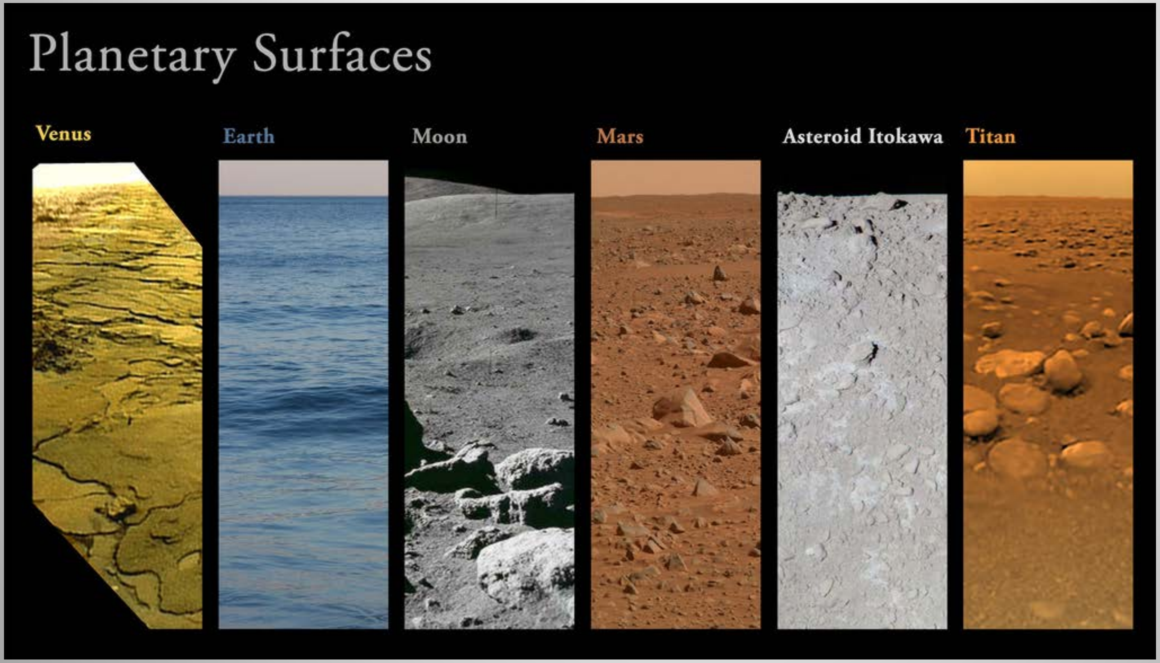
Applications:

- *Quality control of directional effects, e.g., matte, gloss, metallic paints – allows spatial statistics*

Accurate Color – what's it good for?

Applications:

- *Space and planetary exploration*



Research Problems and Questions

Hyperspectral demosaicking

Hyperspectral mosaic patterns

Automatic calibration

Fabrication of accurate color filters

Adaptive color capture (transverse field detector)

High dynamic range sensors and displays

Simultaneous range and color sensors